Radiation Transport Tools for Space Applications: A Review

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Introduction

- Brief discussion of nuclear transport codes widely used in the space radiation community for shielding and scientific analyses:
  - Overview
  - What it can do
  - What it can not do
  - One or two examples of application

Radiation Environments: Particles that should be considered

- Electrons
  - Trapped, solar wind
- Photons
  - Bremsstrahlung, Reactor, RTG, RHU
- Protons
  - Trapped, Solar Energetic Particle Events, GCR
- Neutrons
  - Reactor, RTG, RHU
- Heavy Ions
  - GCR, Solar Energetic Particle Events

Primary Use of Radiation Transport Codes

- Total ionizing dose
  - Cumulative long term ionizing damage
- Displacement damage dose
  - Cumulative long term non-ionizing damage
- Single event effects
  - Event caused by a single charged particle (heavy ions and/or protons) trasversing the active volume of microelectronic devices
- Deep charging

- Particle detector simulation
- Device Simulation

Radiation Transport Codes that will be Covered in this talk

- CREME96
- TRIM
- Integrated Tiger Series (ITS) 3.0
- NOVICE
- MCNP
- MCNPX
- Geant4

General Methods

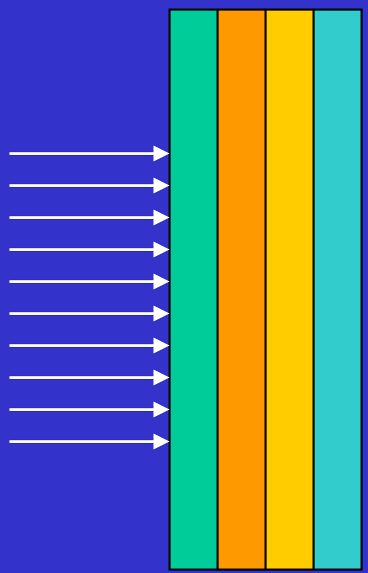
Monte Carlo Method	Deterministic Method
• Does <u>not</u> solve explicit transport equation • Obtain answers by simulating individual particles and recording their average behavior	• Solve transport equation for average particle behavior
• Pros: – Can handle complex geometries – Can handle physically accurate cross sections	• Pros: – Can obtain results throughout problem geometry in one run – Relatively fast even for deep penetration problem
• Cons: – Slow – Results are statistical – Not efficient for deep penetration problems and for space applications	• Cons: – Systematic errors result from discretization of phase space (space, energy, angle) – Only works for geometries for which transport equations can be solved numerically – Must use multi-group cross sections, thus results in inherently less accurate results

Monte Carlo Methods

- Forward vs. Adjoint methods
  - Forward: follows particles from source to target
  - Adjoint: follows particles from target to source
- When are forward calculations more efficient?
  - When we require a large number of responses across the problem geometry from a source confined in relatively small volume
- When are adjoint calculations more efficient?
  - When we require responses over the small volume from a source distributed over large volume or surface

Forward vs. Adjoint (1)

We want to compute energy deposition at each slab (different material) from mono-directional particle source.

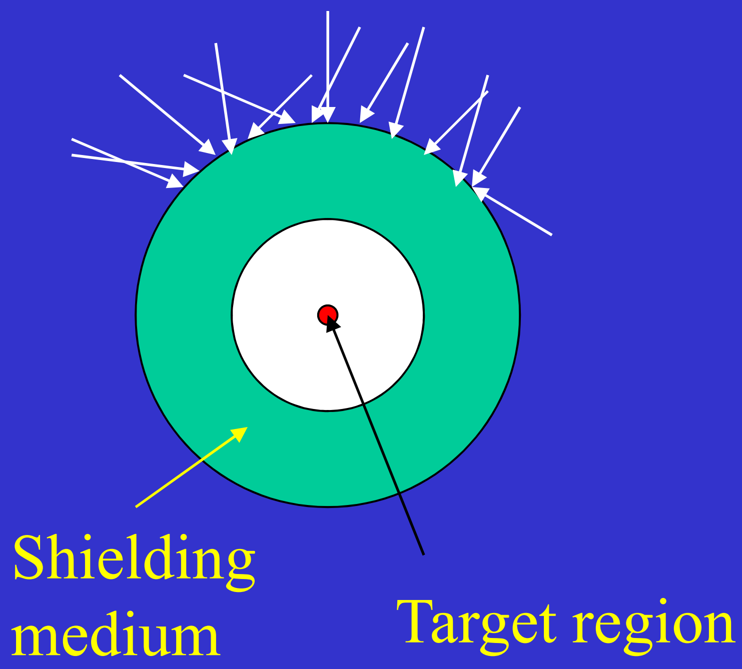


The forward method is more favorable in this situation because every particles simulated will contribute to the results for all 4 slabs.

If we use the adjoint method, this problem implies we have to run 4 separate runs.

Forward vs. Adjoint (2)

We want to compute energy deposition at the small target region located at the center of spherical shell shield..



In forward scheme, many of the source particles will not reach the target region and will not contribute to the results.

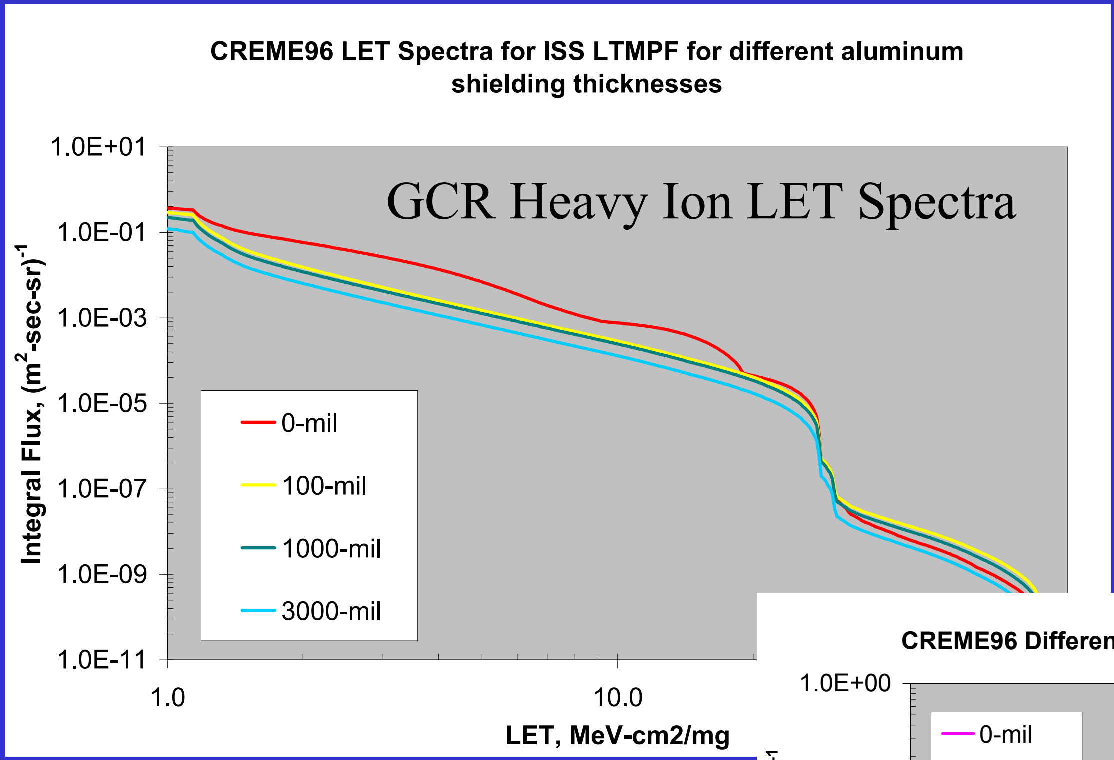
However, in adjoint scheme, every particle simulated will contribute to the results.

Preview

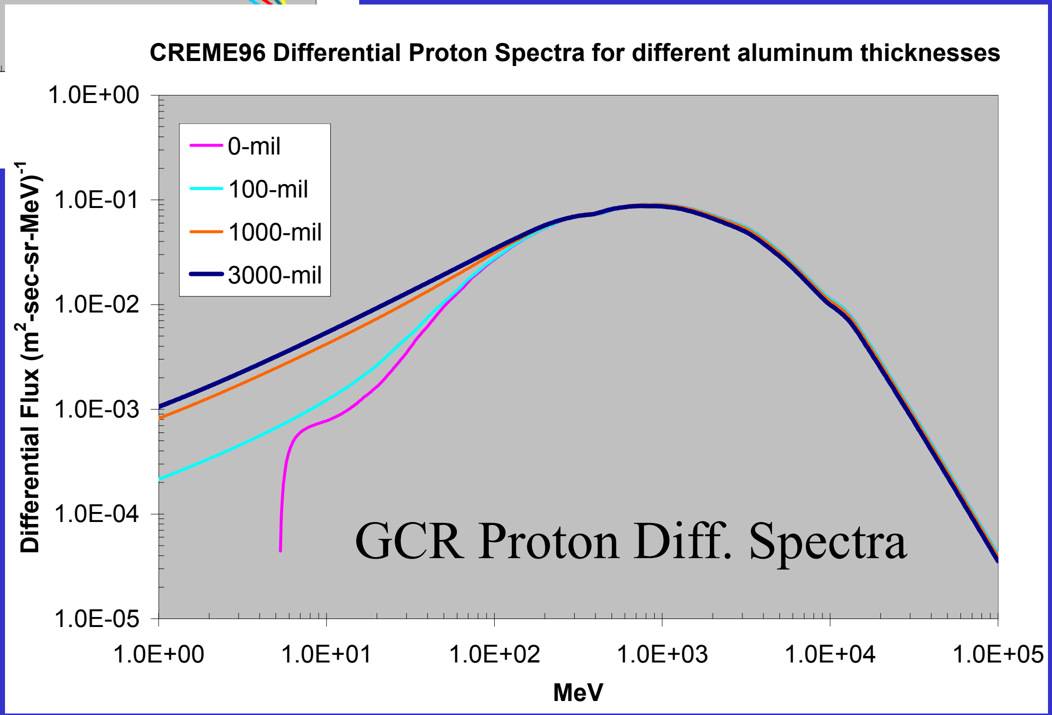
	Electron	Photon	Proton	Neutron	Ion ($Z \geq 2$)
CREME96			Yes		Yes
TRIM			Yes		Yes
ITS	Yes	Yes			
NOVICE	Yes	Yes	Yes		Yes
MCNP	Yes	Yes		Yes	
MCNPX	Yes	Yes	Yes	Yes	Up to Z=2
Geant4	Yes	Yes	Yes	Yes	Yes

CREME96: https://creme96.nrl.navy.mil

- Developed by Naval Research Lab (NRL)
- TRANS module
- 1-Dimension for aluminum
- Particles: All particles treated in CREME96 (protons and heavy ions)
- Primary application:
  - Proton energy spectrum or heavy ion LET spectrum for SEE evaluation of microelectronics
- Pros:
  - Easy web-based user interface
  - Simple physics models for energy loss and nuclear fragmentation
- Cons:
  - Limited to aluminum shielding and 1-dimensional
  - Is the physics accurate?



500 km/51.5 degree Solar Minimum



TRIM: http://www.srim.org/

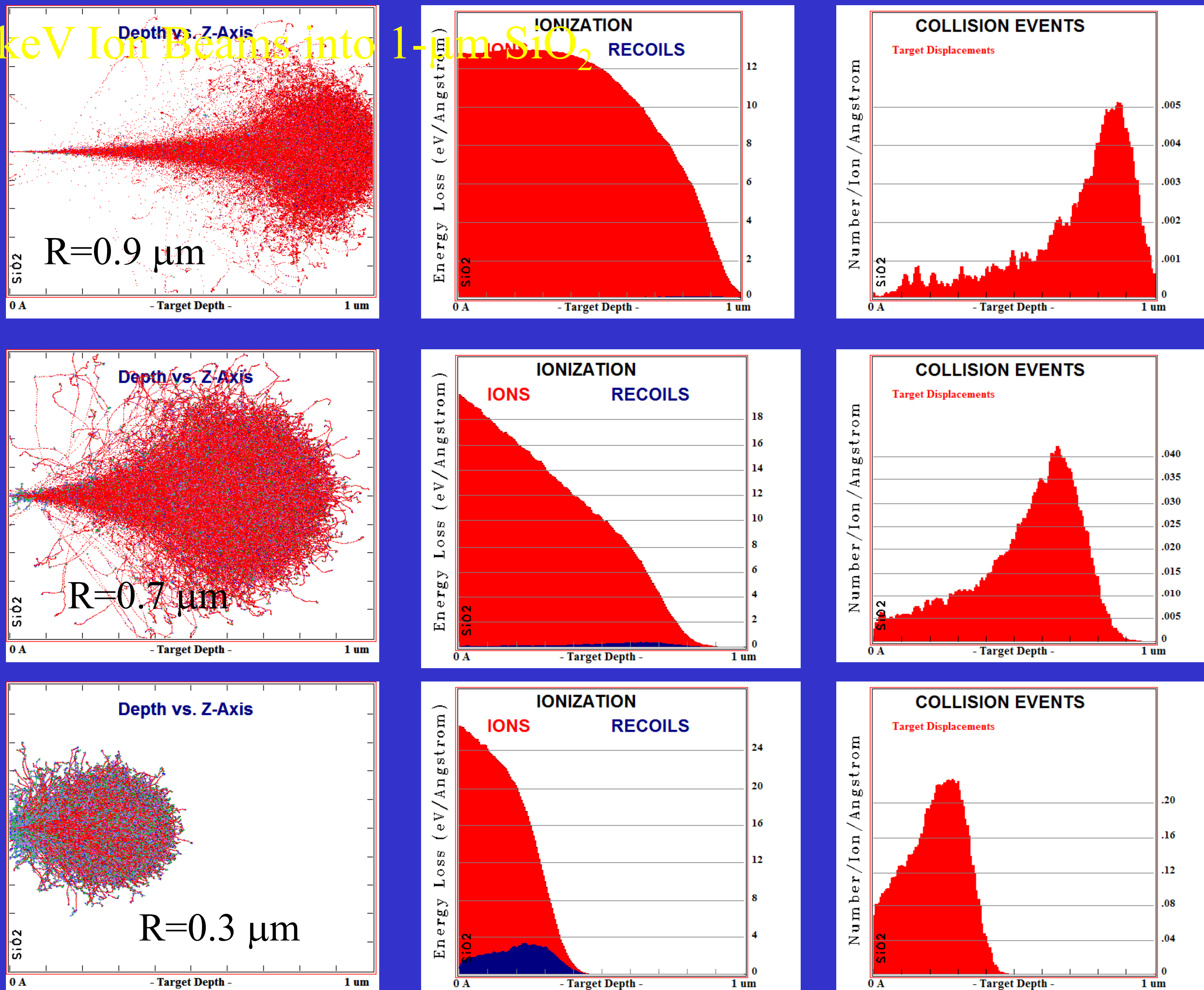
- Developed by James Ziegler
- Monte Carlo (Forward)
- 1-Dimension
- Particles: protons and heavy ions
- Primary application area
  - Proton or heavy ion beam simulation
- Pros:
  - Very simple and easy to learn
  - Cover the whole spectrum of heavy ions
- Cons:
  - Limited in 1-dimensional slab geometry
  - Only Coulomb interaction (no nuclear interaction)

100 keV Ion Beams into 1-μm SiO_2

Proton

Alpha

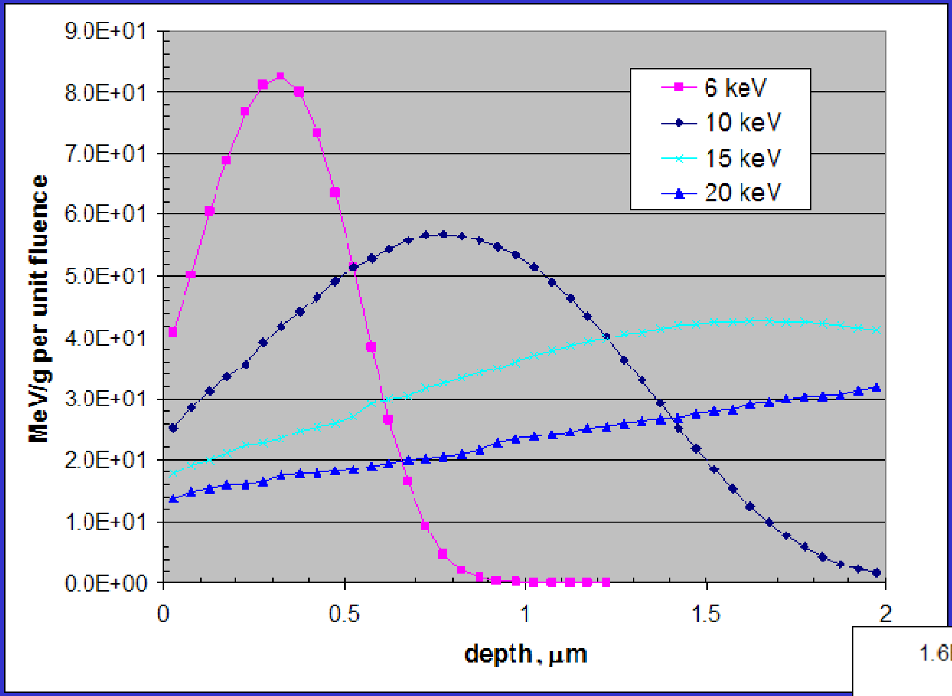
Carbon



ITS3.0: http://www-rsicc.ornl.gov/

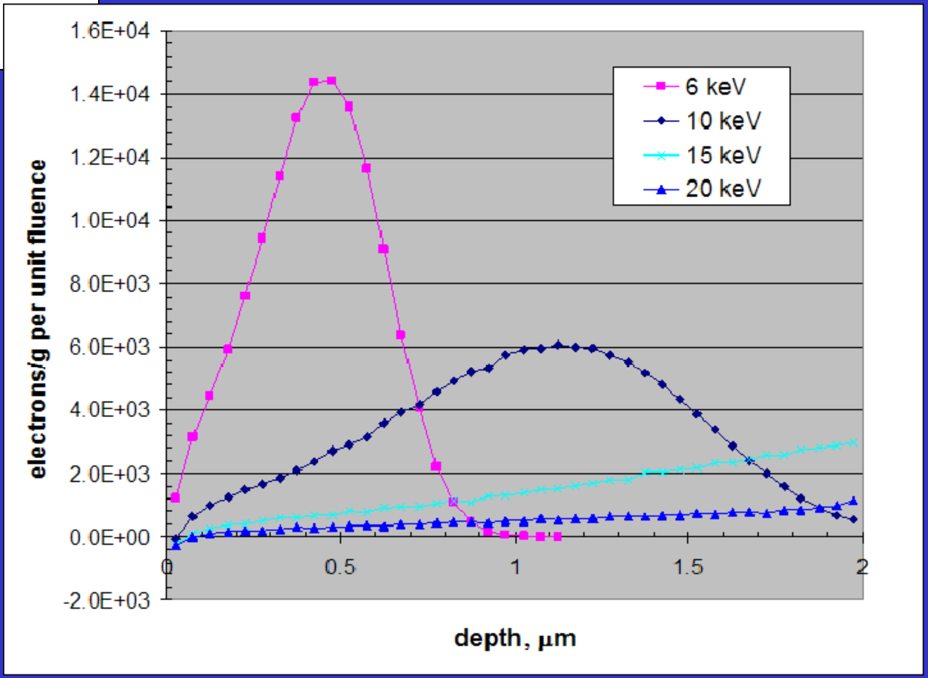
- Developed by Sandia National Lab. (SNL)
  - The latest version is ITS5.0, which is being distributed upon request.
- Monte Carlo (mostly forward)
- 1-D (TIGER), 2-D (CYLTRAN), and 3-D (ACCEPT)
- Primary application
  - Electron/photon beam experiment simulation
- Particles:
  - Electrons and photons
- Pros:
  - Validated physics models
  - Very easy to use (especially for TIGER)
- Cons:
  - Limited geometry modeling, simulation of space environments

Electron Beam into 2 μm Mylar Film



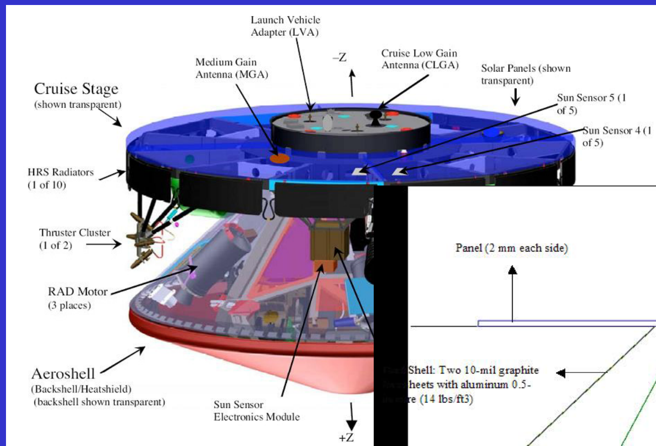
Dose Profile

Charge Deposition Profile



NOVICE: tj@empc.com

- Monte Carlo (adjoint)
  - Specifically developed for space applications
  - Only adjoint code available for charged particle transport
- 3-Dimension
- Primary application
  - Component level analysis with full spacecraft geometry
- Particles:
  - Electrons, protons, photons, heavy Ions
- Pros:
  - Fast
  - Versatile geometry, relatively easy to use
- Cons:
  - Can not handle neutrons, secondary particles
  - Black box (poor user manual)



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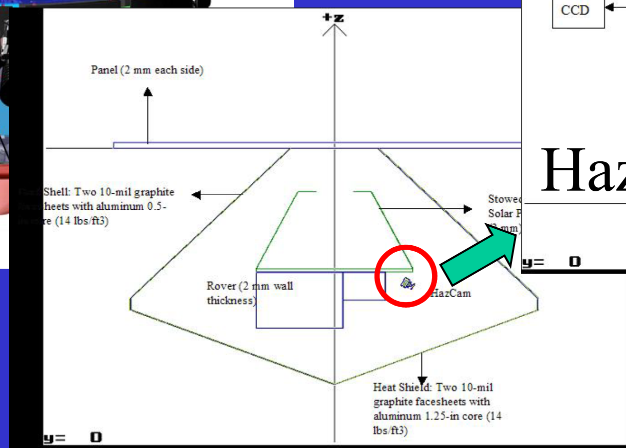
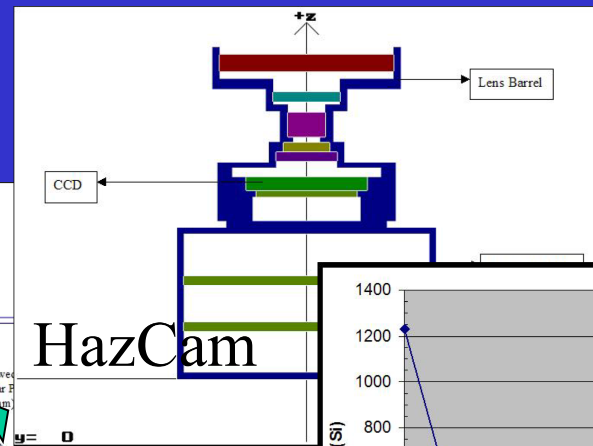
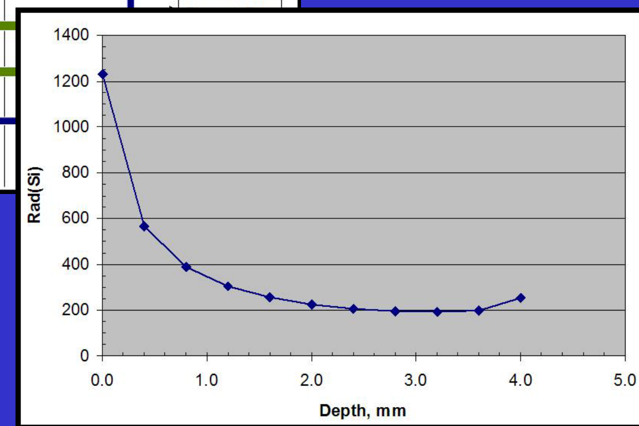
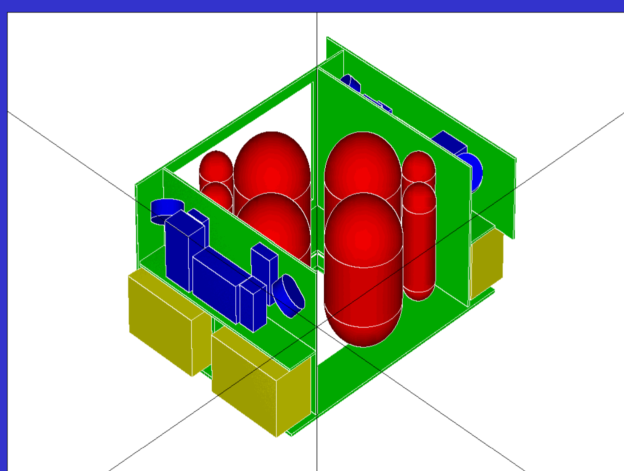
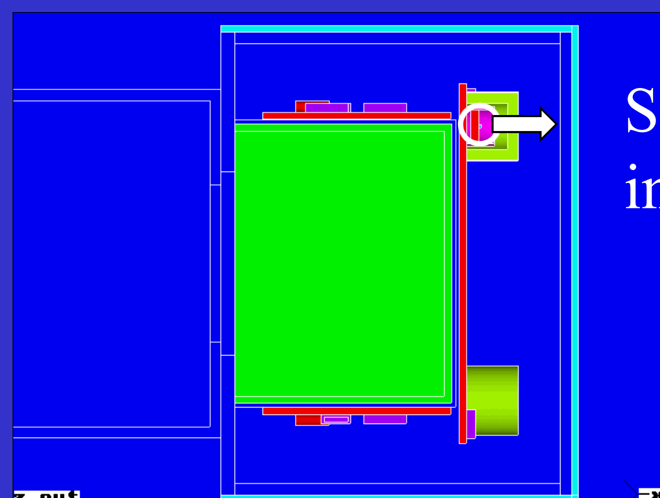




HazCam







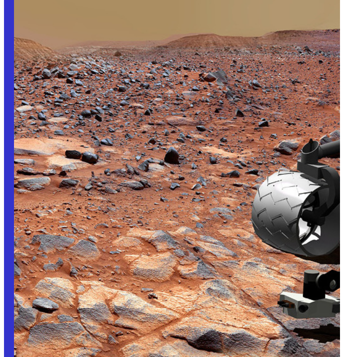
Small device
in a box

MCNP: http://mcnp-green.lanl.gov/index.html

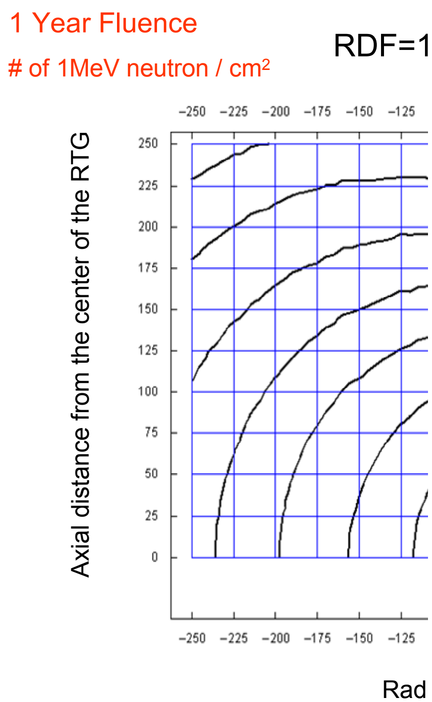
- Developed by Los Alamos National Lab (LANL)
- Monte Carlo (mostly forward)
- 3-Dimensional
- Particles:
  - Neutron, photons, and electrons
- Primary application
  - Neutron/photon transport for RTG and space reactor
- Pros:
  - Extensive history (since the Manhattan Project) and user base
  - Comprehensive physics
  - Versatile geometry and input/output options
- Cons:
  - Relatively difficult to learn
  - Slow for space applications

Mars Science Laboratory

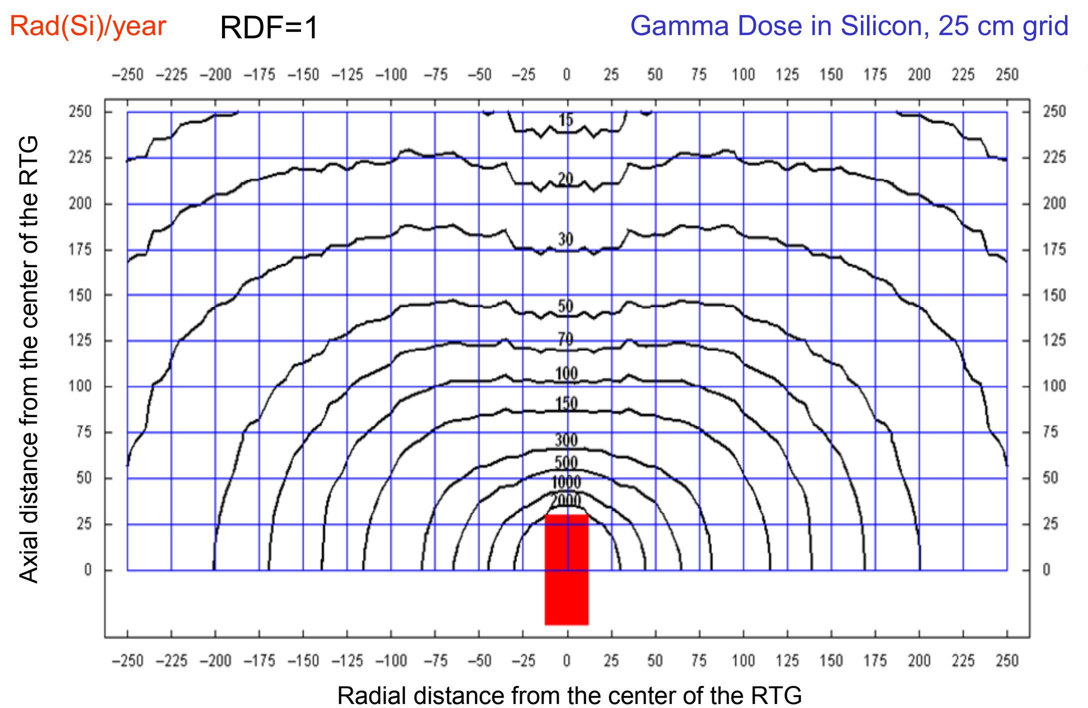
Assessing the present and past habitability of Mars



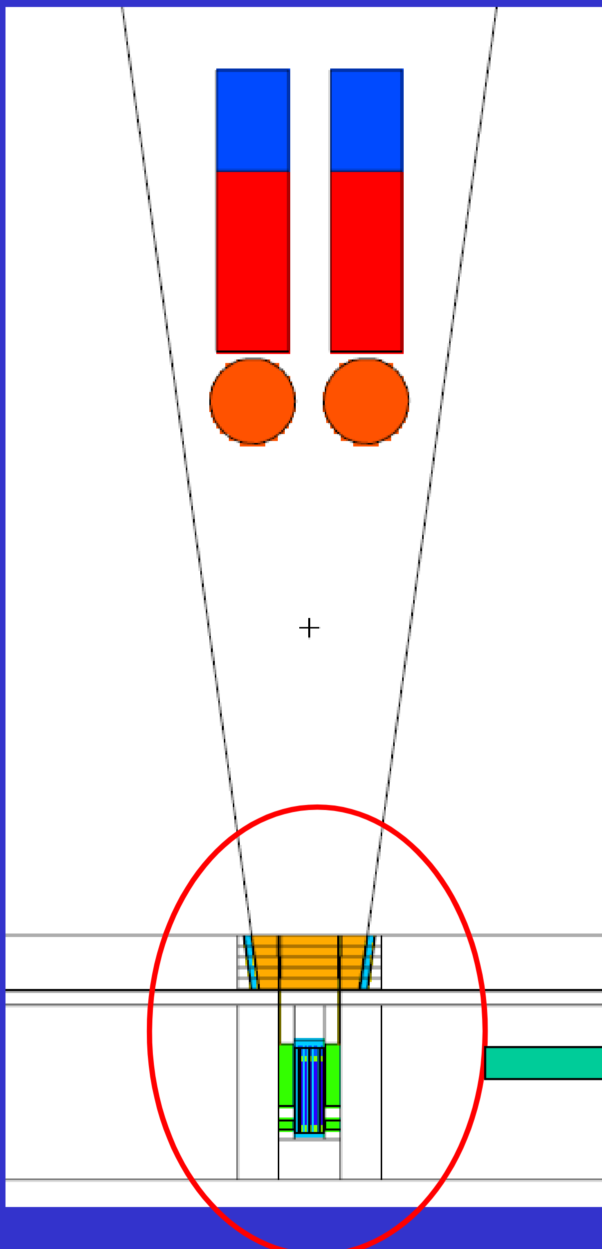
1 MeV Eq. Neutron Fluence Level for 1-Year Operation

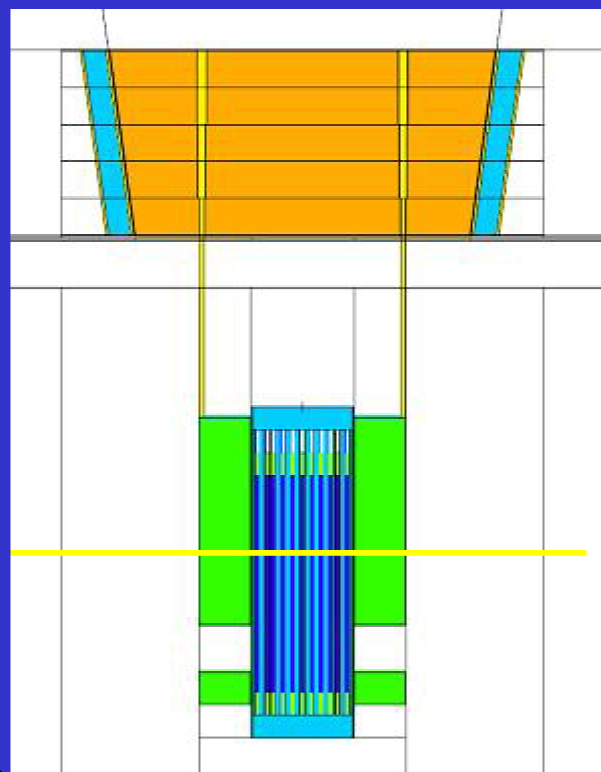


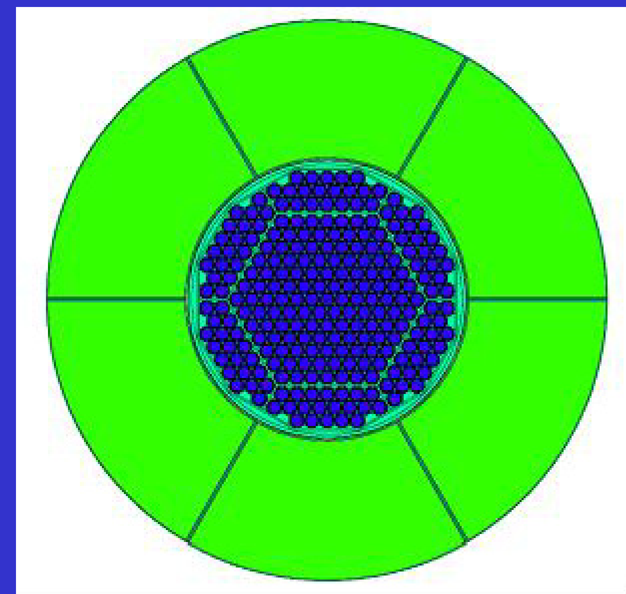
Ionizing Dose Level for 1-Year Operation

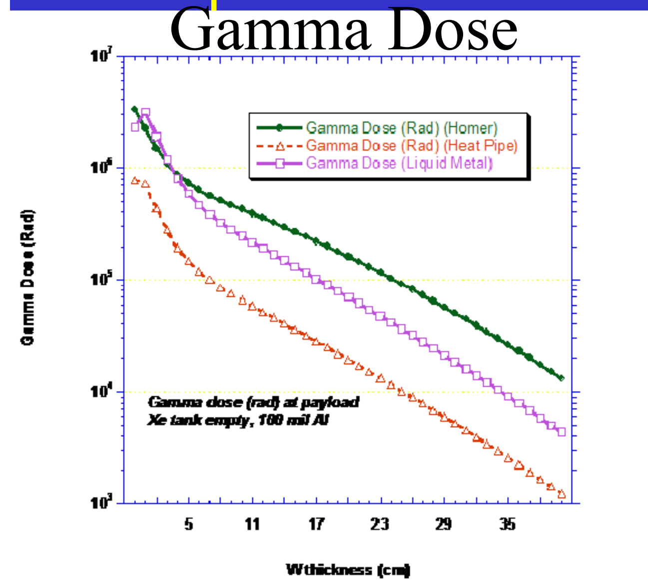


Space Reactor with LiH Shield









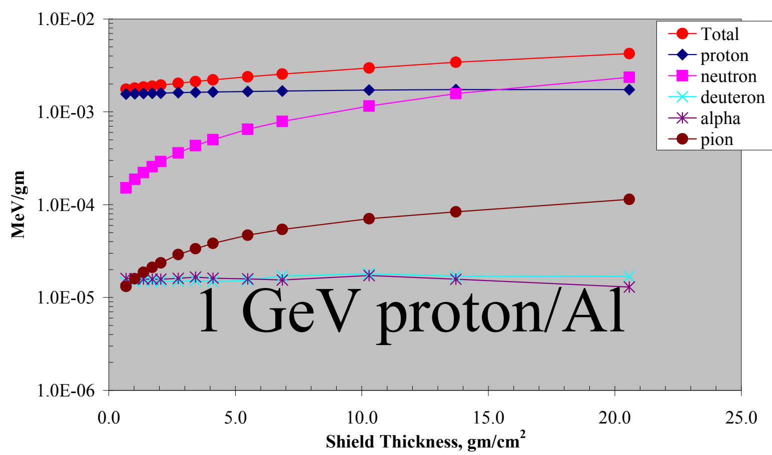
MCNPX: http://mcnpx.lanl.gov/

- Developed by Los Alamos National Lab (LANL)
- Monte Carlo (mostly forward), built upon MCNP
- 3-Dimension
- Particles:
  - Neutrons, anti-neutrons, anti-neutrons, photons, electrons, positrons, muons, anti-muons, electron neutrinos, anti-electron neutrinos, protons, anti-protons, positive pions, negative pions, neutral pions, positive kaons, negative kaons, neutral kaons short, neutral kaons long, deuterons, tritons, helium-3's, and helium-4's

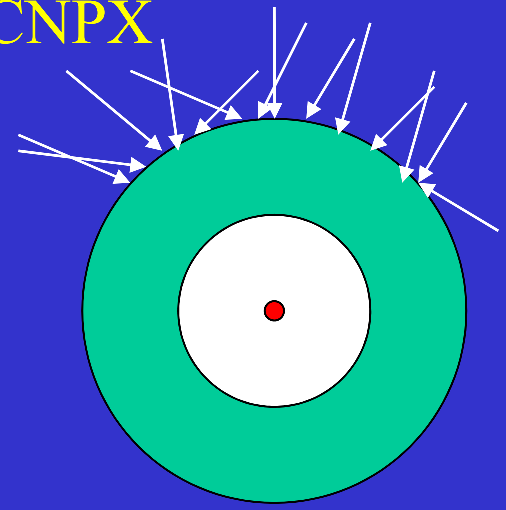
MCNPX (continues)

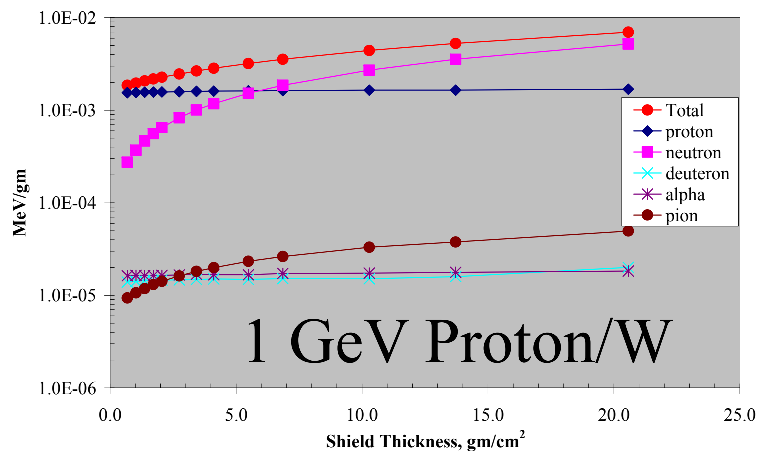
- Primary application
  - Proton transport where secondary particle generation is important
  - Detector simulation
- Pros:
  - Charged particle capability (up to Helium)
  - Capability of treating secondary particle generation
  - Extensive high energy physics
  - Versatile geometry and input/output options
  - <u>Visual output</u>
- Cons:
  - Relatively difficult to learn
  - Slow for space applications

Increase of Displacement Damage Dose due to Secondary Particles Computed by MCNPX

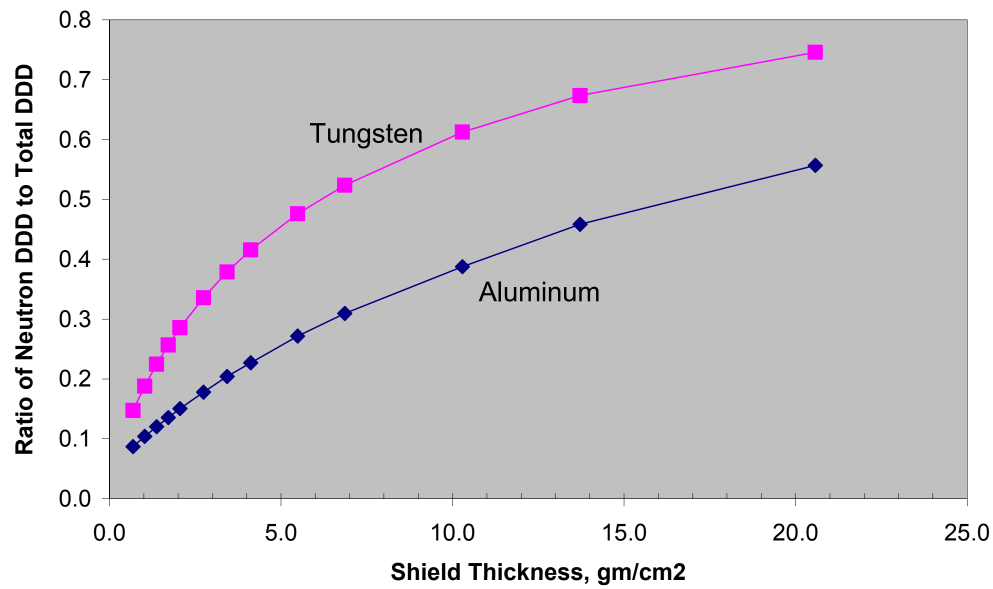


Displacement damage energy deposition profile normalized to 1 proton/cm^2 source strength as a function of aluminum shield thickness for isotropic 1000 MeV protons.





Displacement damage energy deposition profile normalized to 1 proton/cm^2 source strength as a function of tungsten shield thickness for isotropic 1000 MeV protons.

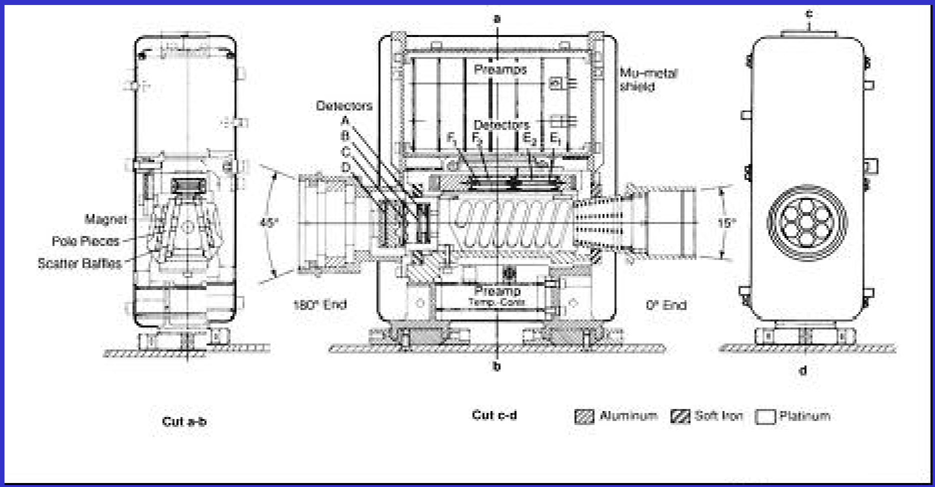


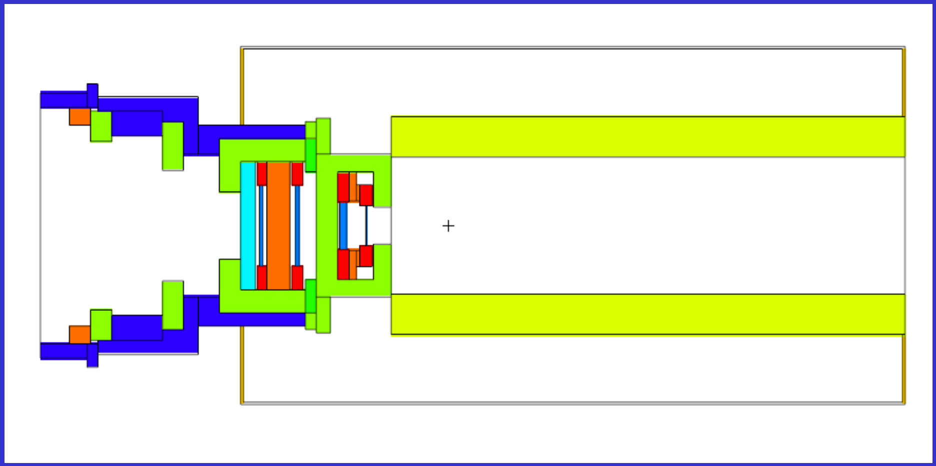
Ratio of the neutron displacement damage to the total displacement damage for the 1000 MeV proton case as a function of shield thickness.

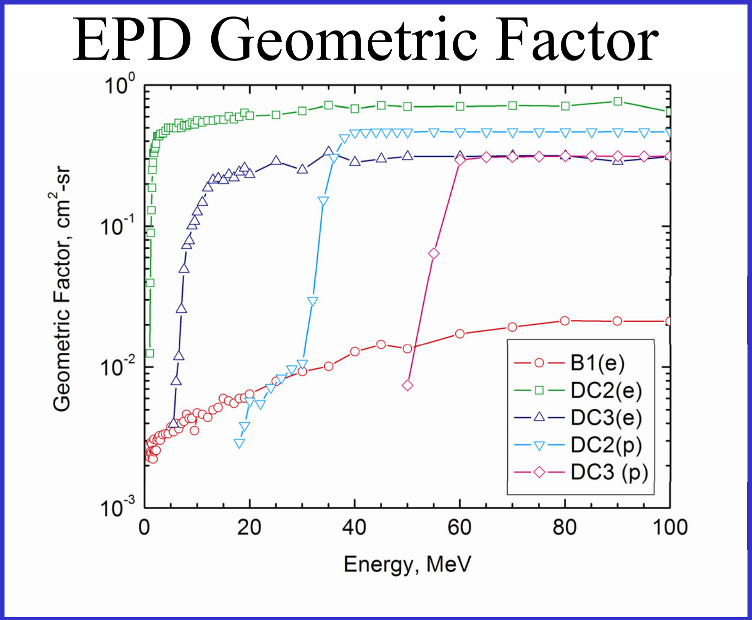
Galileo Energetic Particle Detector

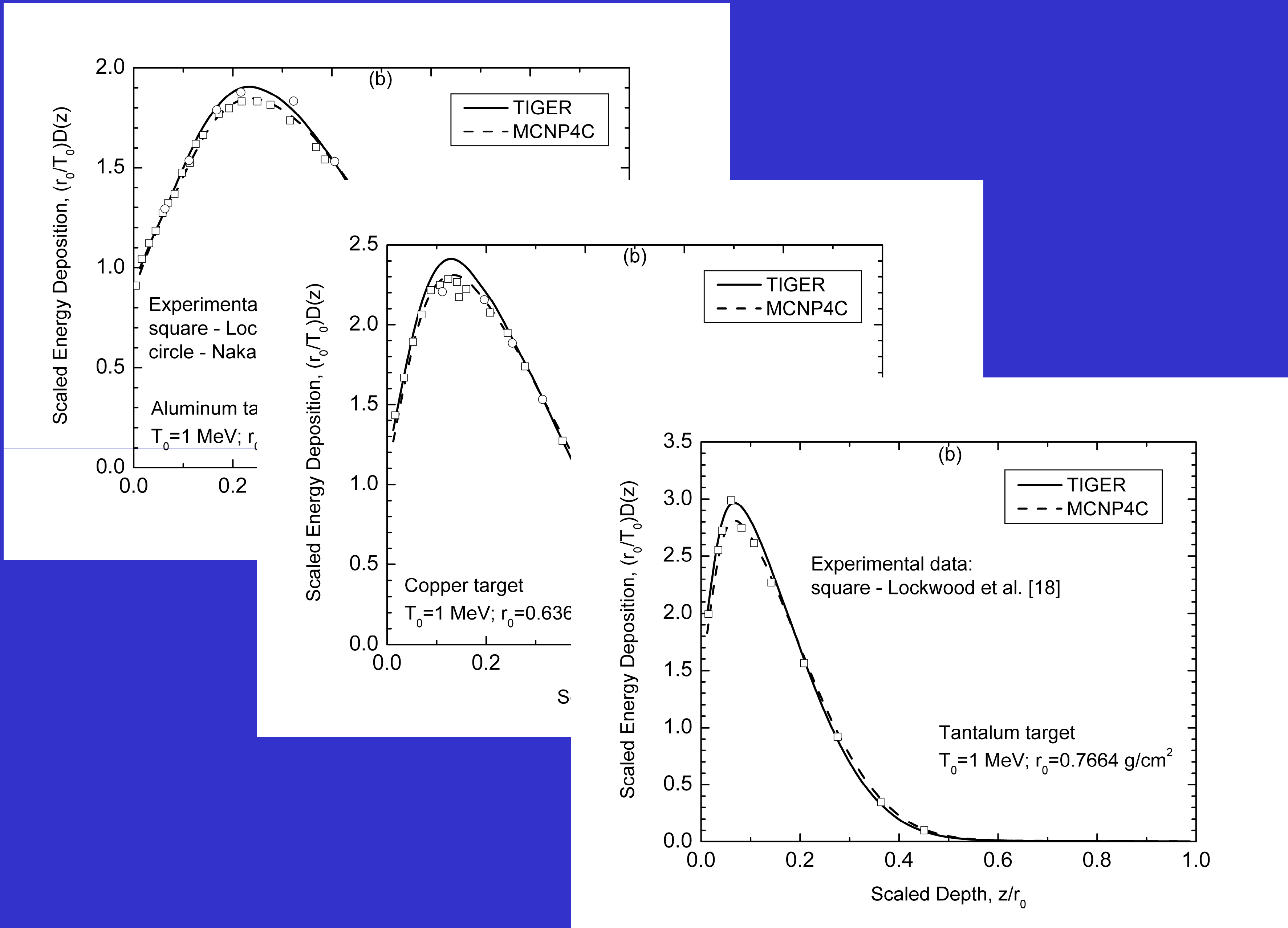
(LEMMS shown here)

EPD=CMS+LEMMS









Scaled Energy Deposition, $(r_0/T_0)D(z)$
(b)
TIGER
MCNP4C
Experimenta
square - Loc
circle - Naka
Aluminum ta
T_0=1 MeV; r_0
Copper target
T_0=1 MeV; r_0=0.636
Experimental data:
square - Lockwood et al. [18]
Tantalum target
T_0=1 MeV; r_0=0.7664 g/cm^2
Scaled Depth, z/r_0

Geant4: http://geant4.web.cern.ch/geant4/

- Developed by CERN
- Monte Carlo (forward)
- 3-Dimension
- Particles:
  - All particles relevant to space environment
- Primary application
  - Detector simulation
  - SEU simulation with TCAD
- Pros:
  - Charged particle capability including heavy ions
  - Capability of secondary particle transport
  - Extensive high energy physics
  - Versatile geometry and input/output options
  - Visual output
  - Extensive, and growing, space user-base:
- Cons:
  - Very difficult to learn
  - Slow for space applications
  - No error bar of results

Application of the RADSAFE Concept

Vanderbilt University

R.A. Reed, R.A. Weller, R.D. Schrimpf, L.W. Massengill,

NASA/GSFC

K.A. LaBel

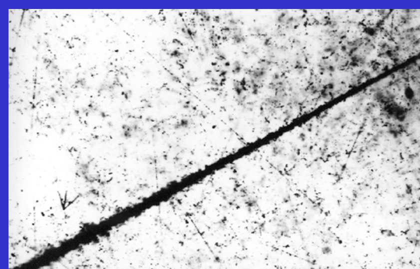
SLAC

M. Asai, D.H. Wright, T. Koi

Single Event Effects

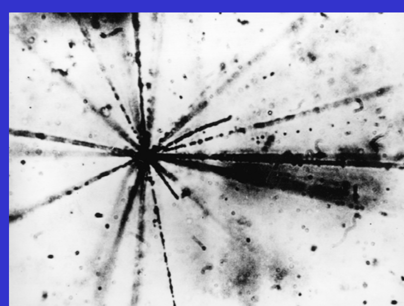
- **Two Ionization Cases:**
  - **Incident particle generates electron-hole (e-h) pairs**

Direct

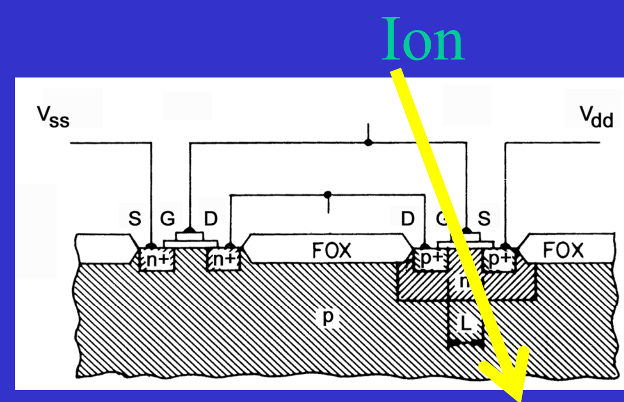


  - **Secondary particles add to generated e-h pairs**

Indirect



P.J McNulty, Notes from 1990 IEEE Nuclear and Space Radiation Effects Conference Short Course



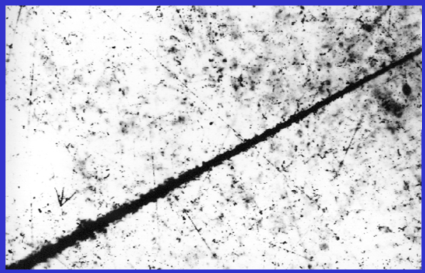
Charge collected on a sensitive node in an electrical circuit causing an unwanted change in information stored on the component

- Single Event Upset
- Single Event Latchup
- Single Event Transient
- Single Event Gate Rupture
- Single Event Functional Interrupt
- Single Event …

Single Event Effects

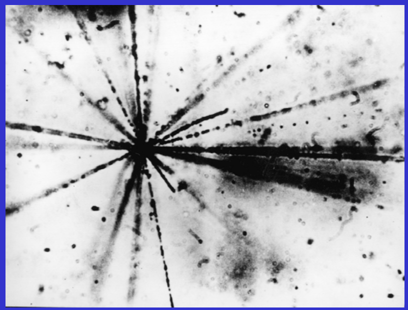
- **Two Ionization Cases:**
  - **Incident particle generates electron-hole (e-h) pairs**

Direct



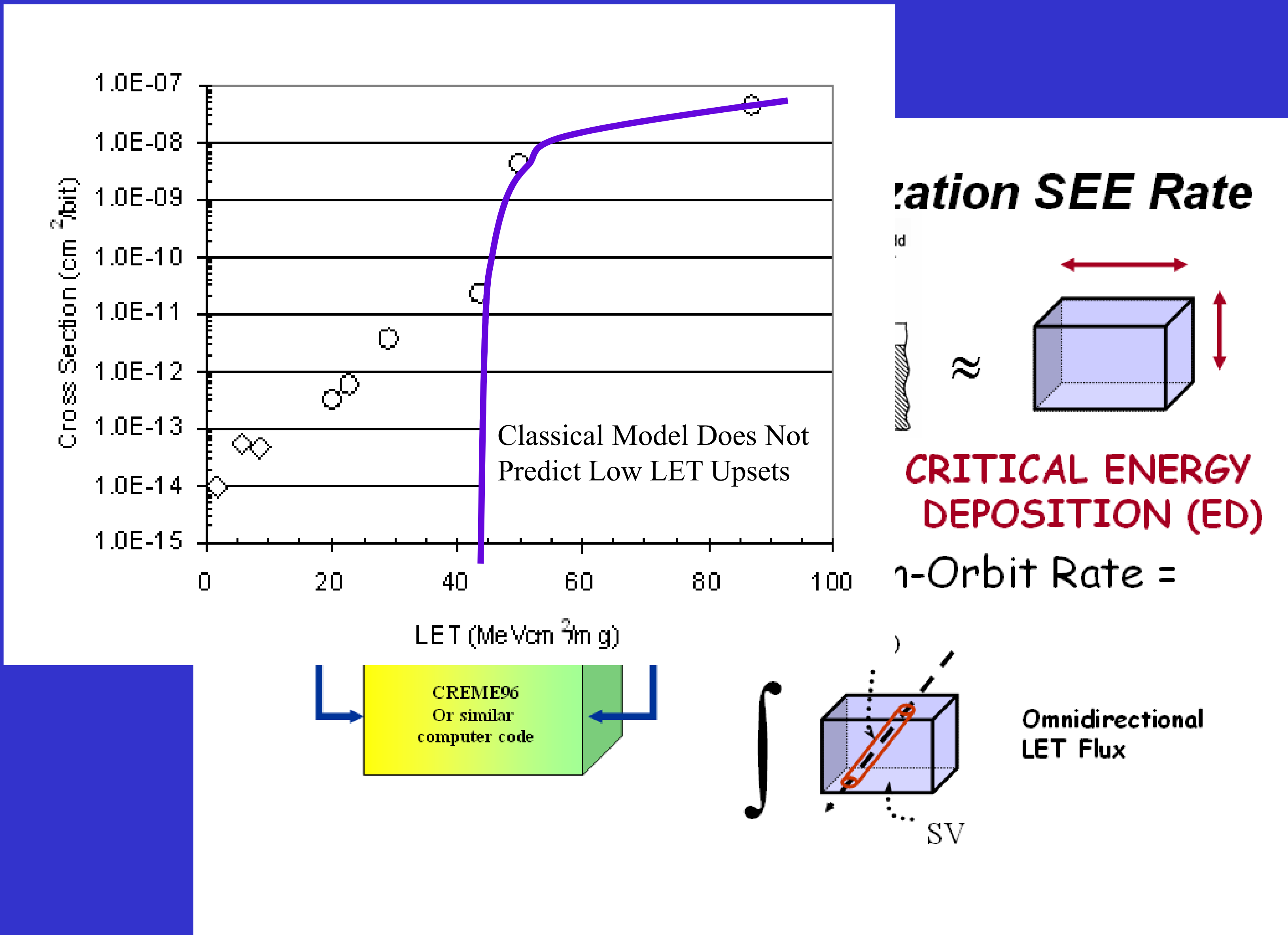
  - **Secondary particles add to generated e-h pairs**

Indirect

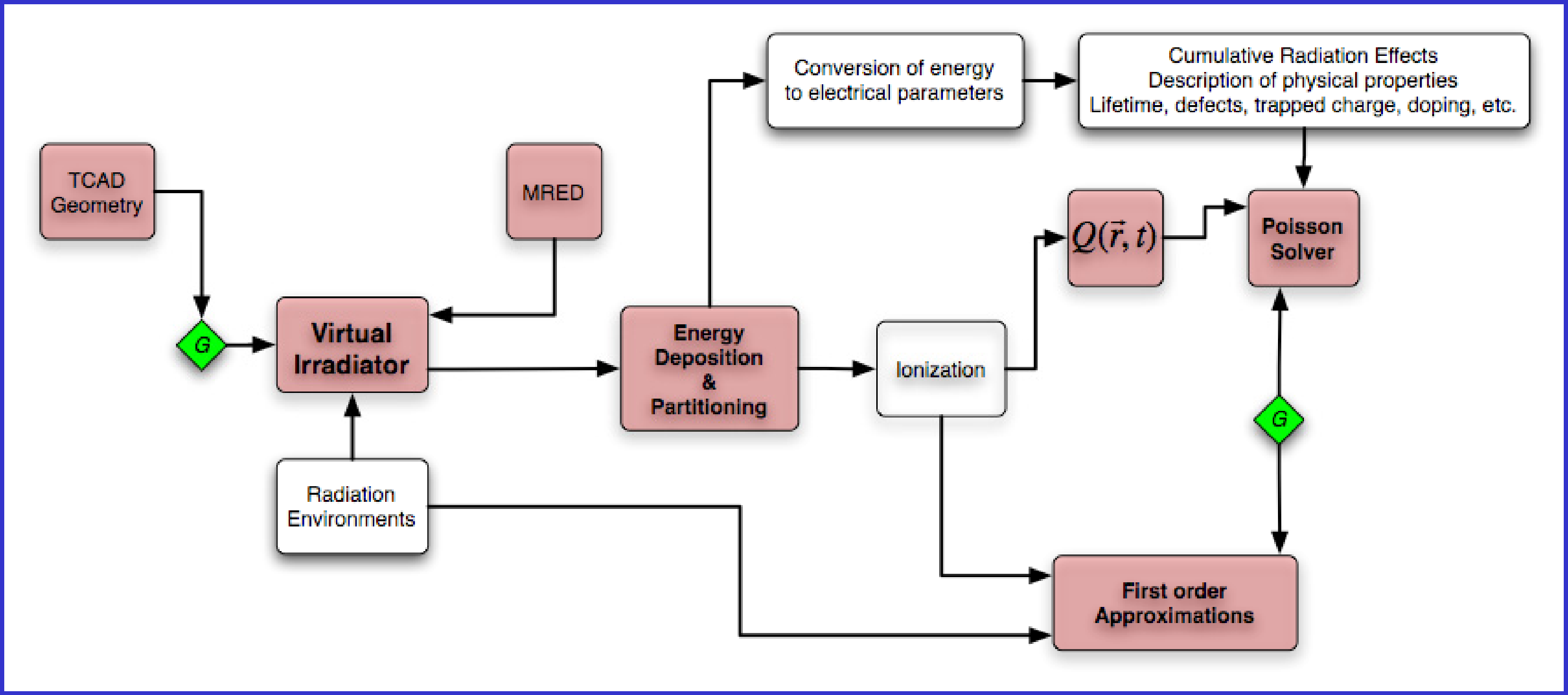


P.J McNulty, Notes from 1990 IEEE Nuclear and Space Radiation Effects Conference Short Course

- **SEE modeling challenges we are currently addressing with RADSAFE:**
  - **Detailed device and circuit response**
    - **Technology Computer Aided Design (TCAD) + Geant4 + spice**
    - **Commercial tools unable to predict indirect ionization case**
  - **On-orbit rate prediction**
    - **Approximation methods**
    - **Failure of models when applied to emerging technology**


1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
1.0E-15
0
20
40
60
80
100
Cross Section (cm 2/bit)
LET (MeVcm 2/mg)
Classical Model Does Not
Predict Low LET Upsets
ation SEE Rate
≈
CRITICAL ENERGY
DEPOSITION (ED)
-Orbit Rate =
CREME96
Or similar
computer code
Omnidirectional
LET Flux
SV

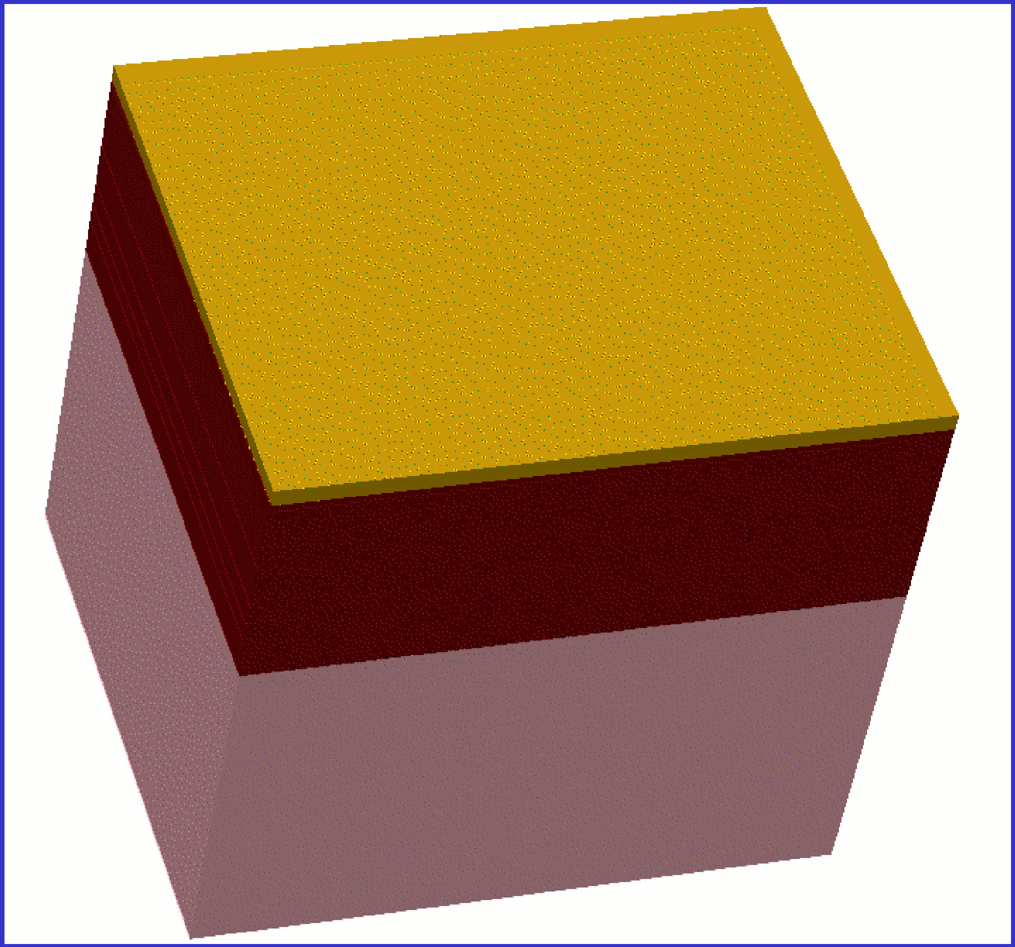
The RADSAFE System: Current Focus



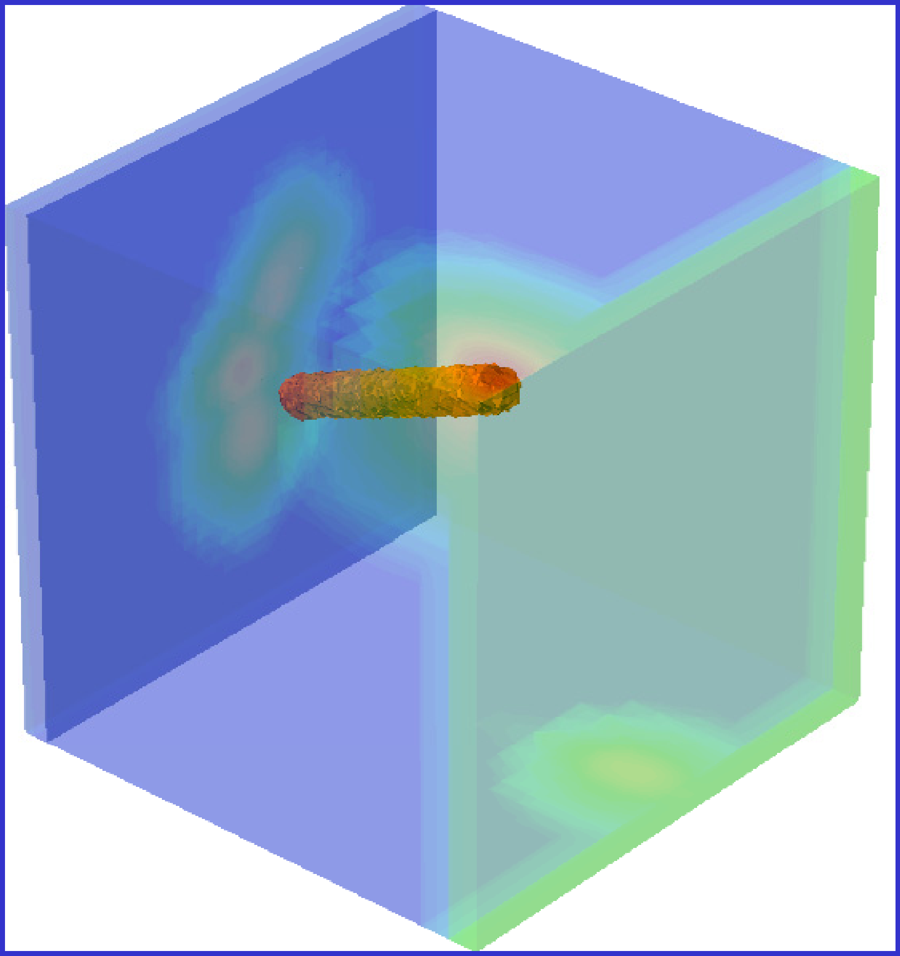
MRED - Monte Carlo Radiative Energy Deposition tool

- Developed at Vanderbilt University
- Based on Geant4
- Run time selectable physics list
- Python interface
- Highly Flexible output

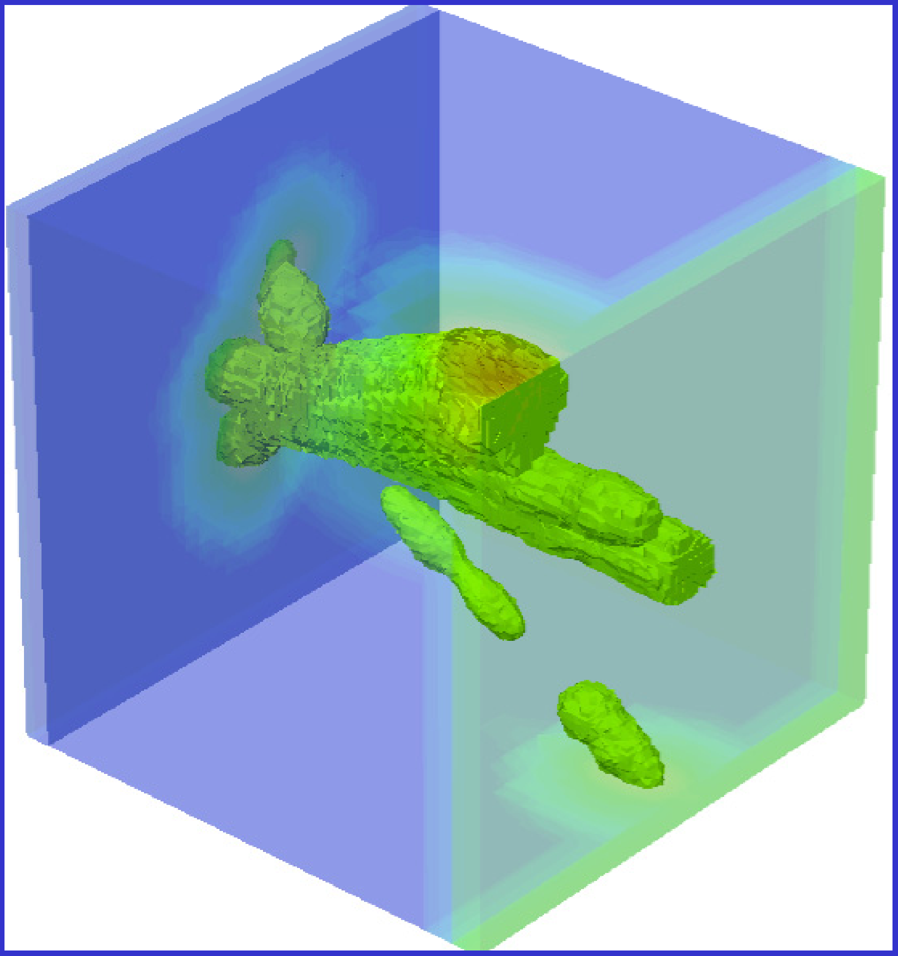
Example: SEUs in SRAMS



Ion Tracks

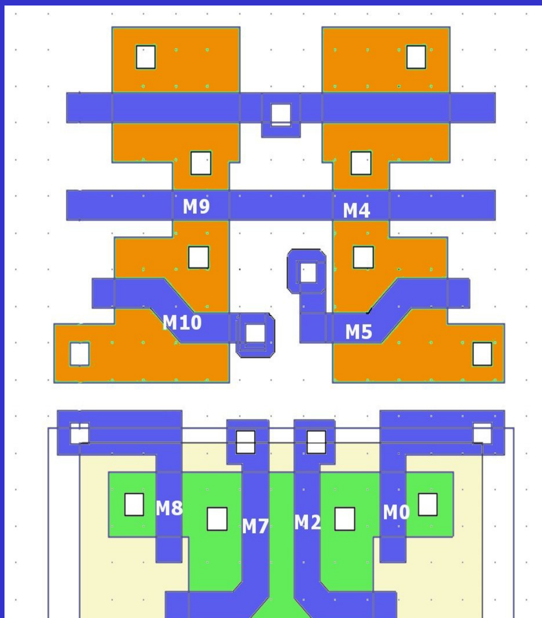


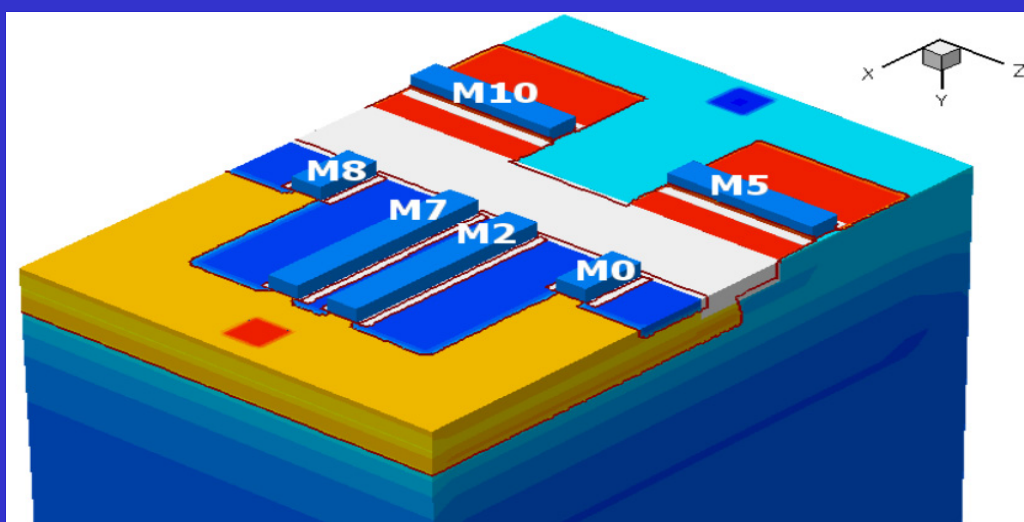
10^{18} e^-/cm^3



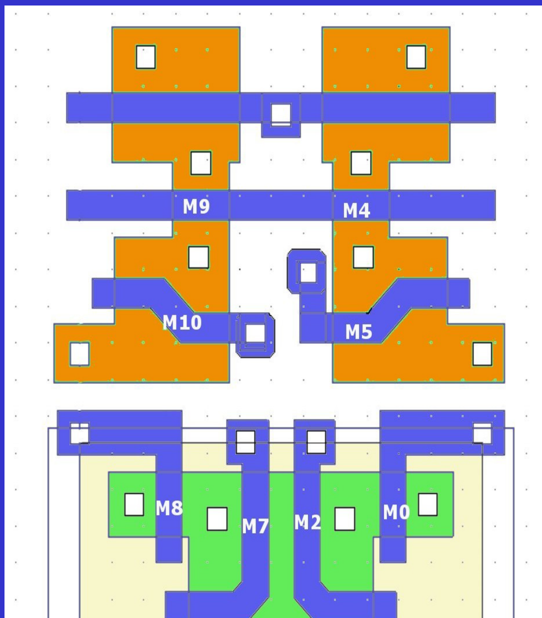
10^{14} e^-/cm^3

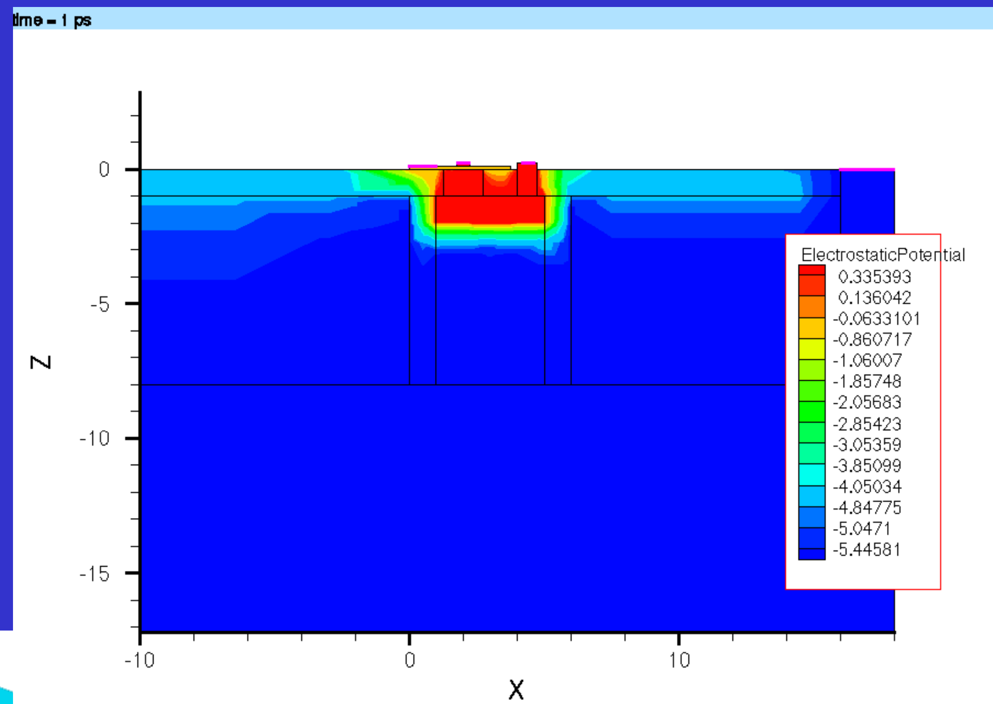
TCAD simulation of radiation event

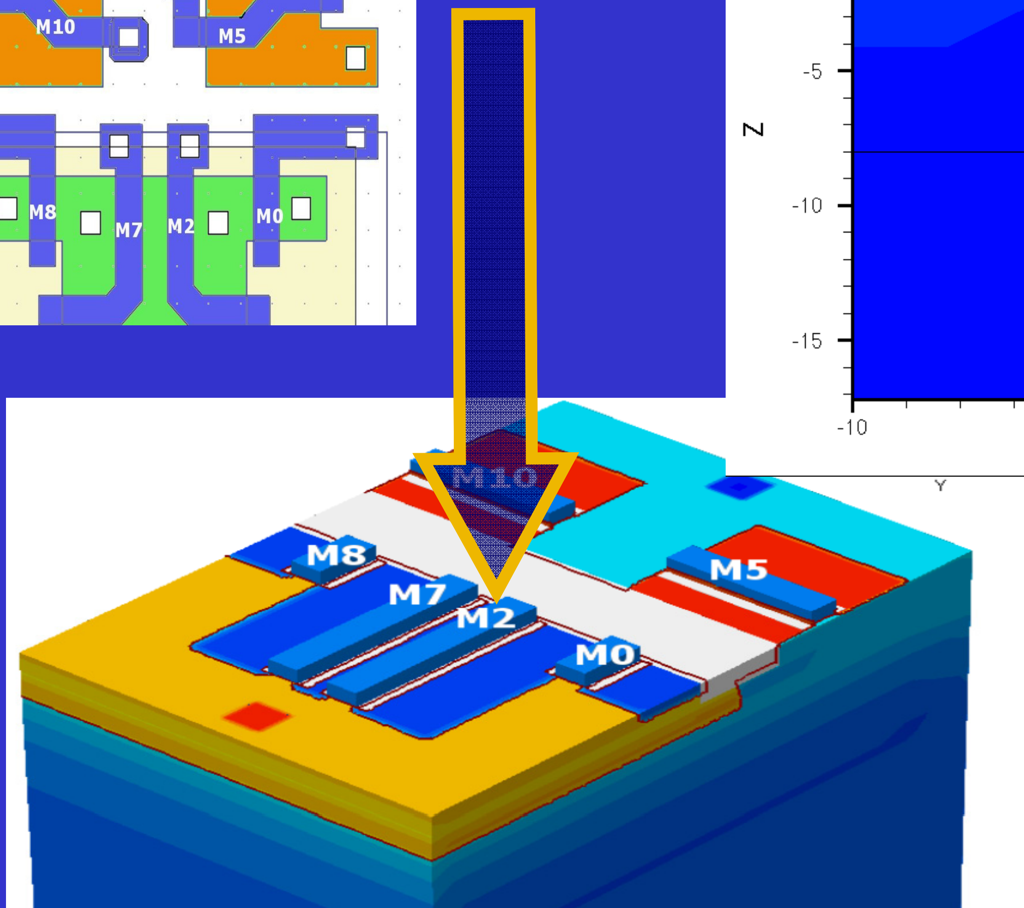




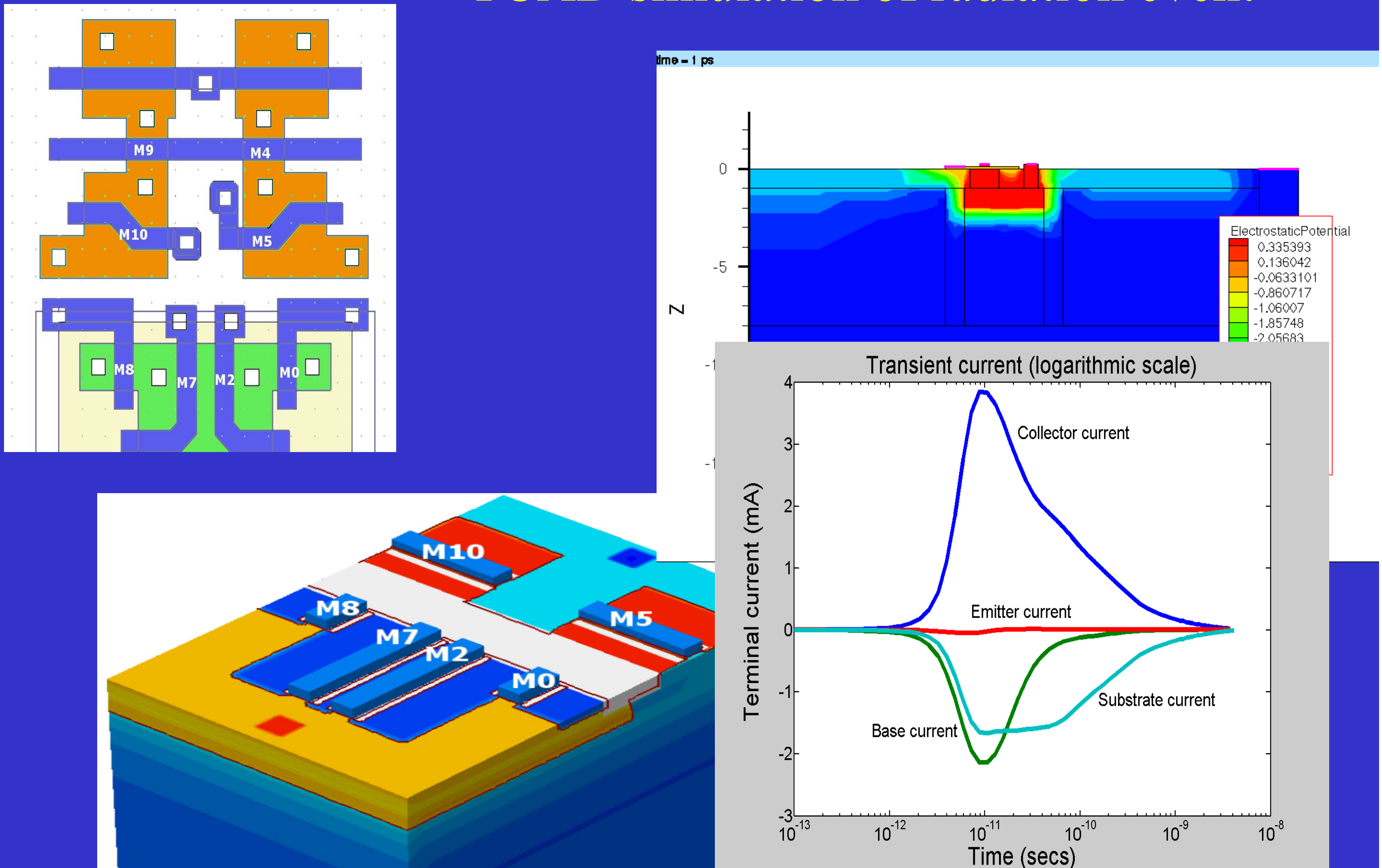
TCAD simulation of radiation event

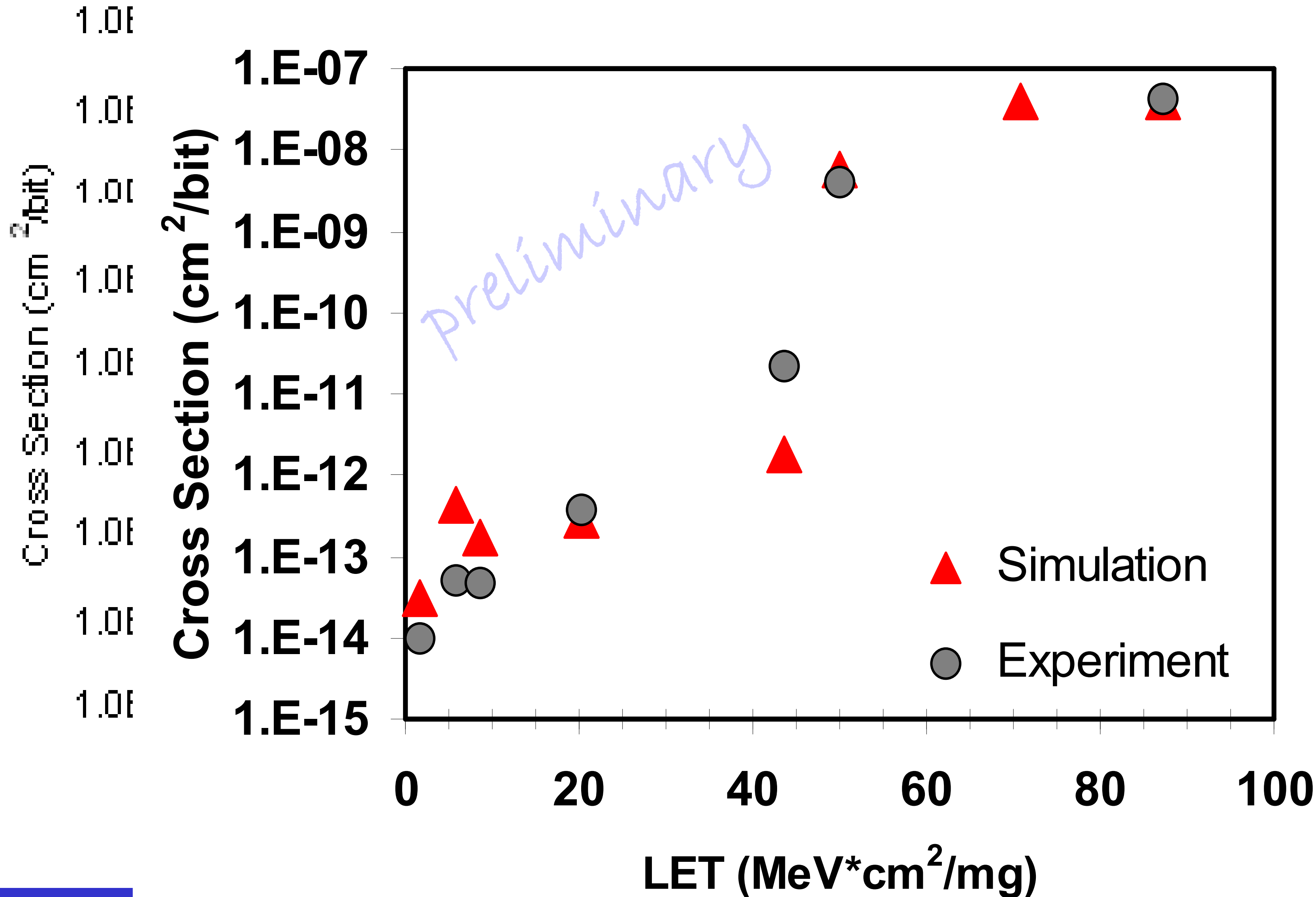






TCAD simulation of radiation event





1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
1.E-12
1.E-13
1.E-14
1.E-15
Cross Section (cm^2/bit)
0
20
40
60
80
100
LET (MeV*cm^2/mg)
Simulation
Experiment
preliminary

Conclusion

- Careful code selection for specific situation is required for correct answer.
  - Some of the codes may be easy to learn and run, but may need correct interpretation of output.
- My personal view of what we need to do in the future:
  - To develop an adjoint Monte Carlo code (independent of NOVICE)
  - To improve heavy ion capability
  - To expand to lower (< 1 keV) energy
- Radiation transport codes not covered today:
  - EGS4, CEPXS, HZETRN, PENELOPE, FLUKA, MARS, …..

Summary

		Primary Application	Particles
CREME96	1-D	Single Event Effects	Proton and all heavy ions
TRIM	1-D	Beam Simulation for dose and damage profile	Proton and all heavy ions (Coulomb only)
ITS	3-D	Beam simulation for dose and charging profile (TIGER)	Electron and photon
NOVICE	3-D	Component level analysis with complex spacecraft geometry	Electron, photons, and heavy ions
MCNP	3-D	RTG and space reactor simulation	Neutron, photon, and electron
MCNPX	3-D	Secondary particle simulation, science instrument simulation	Neutron, photon, electron, and helium
Geant4	3-D	Secondary particle simulation, science instrument simulation, device simulation	All particles relevant to space environment